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Some recent results on Schrödinger equations with time-periodic potentials

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1 Introduction. Statement of Results

We report on some recent results on Schrödinger equations with time-periodic potentials. The full report on the results will be published in [1]. We consider the Schrödinger equation

$$i\partial_t u = (-\Delta + V(t, x)) u, \quad (t, x) \in \mathbf{R} \times \mathbf{R}^3. \quad (1.1)$$

Note that the results presented here depend on the configuration space being of dimension three.

We make the following assumption on the potential $V(t, x)$. We write $\mathbf{T} = \mathbf{R}/2\pi\mathbf{Z}$ for the unit circle and let $\langle x \rangle = (1 + x^2)^{1/2}$.

Assumption 1.1. *The function $V(t, x)$ is real-valued and is 2π -periodic with respect to t : $V(t, x) = V(t + 2\pi, x)$. For $\beta > 2$ we assume that*

$$\sum_{j=0}^2 \sup_{x \in \mathbf{R}^3} \langle x \rangle^\beta \left(\int_0^{2\pi} |\partial_t^j V(t, x)|^2 dt \right)^{\frac{1}{2}} < \infty. \quad (1.2)$$

Associated with the equation (1.1) is a unitary propagator $U(t, s)$, which is a family of unitary operators on $\mathcal{H} = L^2(\mathbf{R}^3)$ with the following properties. We let $H^2(\mathbf{R}^3)$ denote the usual Sobolev space of order 2.

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1. $(t, s) \mapsto U(t, s)$ is strongly continuous.
2. $U(t, r) = U(t, s)U(s, r)$ for all $t, s, r \in \mathbf{R}$.
3. $U(t + 2\pi, s + 2\pi) = U(t, s)$ for all $t, s \in \mathbf{R}$.
4. $U(t, s)H^2(\mathbf{R}^3) = H^2(\mathbf{R}^3)$. For $u_0 \in H^2(\mathbf{R}^3)$, $U(t, s)u_0$ is an \mathcal{H} -valued C^1 -function of (t, s) , which satisfies

$$\begin{aligned} i\partial_t U(t, s)u_0 &= H(t)U(t, s)u_0, \\ i\partial_s U(t, s)u_0 &= -U(t, s)H(s)u_0. \end{aligned}$$

To study the properties of $U(t, s)$ in detail one introduces the extended phase space $\mathcal{K} = L^2(\mathbf{T} \times \mathbf{R}^3) \equiv L^2(\mathbf{T}; \mathcal{H})$. Define

$$\begin{aligned} K_0 &= -i\partial_t - \Delta, \\ K &= -i\partial_t - \Delta + V(t, x). \end{aligned}$$

These operators are self-adjoint on \mathcal{K} , on the natural domain. The relation to the propagator is as follows. Let $\mathcal{U}(\sigma) = e^{-i\sigma K}$. Then

$$(\mathcal{U}(\sigma)u)(t) = U(t, t - \sigma)u(t - \sigma)$$

for $u = u(t, \cdot) \in \mathcal{K}$. The extended phase space formalism was introduced by Howland in [2], and implemented for the time-periodic case by Yajima in [6].

One of the problems considered in [1] is the large time behavior of a solution $u(t) = U(t, 0)u_0$. The usual approach is to use scattering theory. Let $\lambda_j \in [0, 1)$ be eigenvalues of K with eigenfunctions φ_j (the spectrum of K is invariant under integer translations). Under the above conditions the wave operators exist and are complete:

$$W_{\pm} = s\text{-}\lim_{t \rightarrow \pm\infty} U(0, t)e^{-itH_0}, \quad H_0 = -\Delta.$$

Completeness means that $\text{Ran } W_{\pm} = \mathcal{H}_{\text{ac}}(\mathcal{U}_0)$ and $\mathcal{H}_{\text{sc}}(\mathcal{U}_0) = \{0\}$. Here $\mathcal{U}_0 = U(2\pi, 0)$ denotes the monodromy (Floquet) operator. Consequently $u(t) = U(t, 0)u_0$ can be written as

$$u(t, x) = \sum a_j e^{-it\lambda_j} \varphi_j(t, x) + u_{\text{scat}}(t, x),$$

where

$$\|u_{\text{scat}}(t, x) - e^{-itH_0}\psi(x)\| \rightarrow 0 \quad \text{for } t \rightarrow \infty$$

for some $\psi \in \mathcal{H}$. Actually, these results hold under the short range assumption $\beta > 1$ in (1.2), see [6], [3], [7].

Here we consider a different approach to the large time behavior of a solution. Let for $\delta \in \mathbf{R}$

$$\mathcal{H}_\delta = L^2_\delta(\mathbf{R}^3) = \{f \in L^2_{\text{loc}}(\mathbf{R}^3) \mid \langle x \rangle^\delta f(x) \in L^2(\mathbf{R}^3)\}$$

denote the weighted spaces. Then we take $u_0 \in \mathcal{H}_\delta$ for a sufficiently large $\delta > 0$, and look at the solution $U(t, 0)u_0$ in the space $\mathcal{H}_{-\delta}$.

To state our results we introduce the weighted Sobolev spaces

$$\mathcal{K}_\delta^s = H^s(\mathbf{T}, \mathcal{H}_\delta),$$

where s is a nonnegative integer, and $\delta \in \mathbf{R}$. We introduce the following definition:

Definition 1.2. $n \in \mathbf{Z}$ is said to be a threshold resonance of K , if there exists a solution $u(t, x)$ of the equation

$$-i\partial_t u - \Delta u + Vu = nu,$$

such that, with a constant $C \neq 0$,

$$u(t, x) = \frac{Ce^{int}}{|x|} + u_1(t, x), \quad u_1 \in \mathcal{K}.$$

Such a solution is called an n -resonant solution.

The main results on the large time behavior of a solution can be stated as follows:

Theorem 1.3. Let $\beta_k = \max\{2k+1, 4\}$. Let V satisfy the Assumption 1.1 for some $\beta > \beta_k$, $k \in \mathbf{N}$, and let $\{\phi_j\}$ be an orthonormal basis of eigenfunctions of K corresponding to the eigenvalues $0 \leq \lambda_j < 1$. Set $\delta = \beta/2$ and $\varepsilon_0 = \min\{1, \frac{\beta-\beta_k}{2}\}$. We have the following results.

(1) Suppose K has neither threshold resonances nor integer eigenvalues. Then there exist finite rank operators B_1, \dots, B_k from \mathcal{H}_δ to $\mathcal{K}_{-\delta}^1$, such that $B_j = 0$, unless j is odd, and such that, for any $u_0 \in \mathcal{H}_\delta$, and for any ε , $0 < \varepsilon < \varepsilon_0$, as $t \rightarrow \infty$,

$$\begin{aligned} U(t, 0)u_0 = \sum_j c_j e^{-it\lambda_j} \phi_j(t, x) + t^{-\frac{3}{2}} B_1 u_0(t, x) + \dots \\ \dots + t^{-\frac{k}{2}-1} B_k u_0(t, x) + O(t^{-\frac{k+\varepsilon}{2}-1}), \end{aligned}$$

where $c_j = 2\pi(\phi_j(0), u_0)_{\mathcal{H}}$, and $O(t^{-\frac{k+\varepsilon}{2}-1})$ stands for an $\mathcal{H}_{-\delta}$ -valued function of t such that its norm in $\mathcal{H}_{-\delta}$ is bounded by $C t^{-\frac{k+\varepsilon}{2}-1} \|u_0\|_{\mathcal{H}_\delta}$, when $t \geq 1$.

(2) Suppose K has either threshold resonances, integer eigenvalues, or both, and assume that $\beta > \beta_k$, $k \geq 2$. Furthermore, $\{\phi_{01}, \dots, \phi_{0m}\} \subset \{\phi_j\}$ is an orthonormal basis of eigenfunctions of K with eigenvalue 0. Then there exist a 0-resonant solution $\psi(t, x)$, finite rank operators B_1, \dots, B_{k-2} from \mathcal{H}_δ to $\mathcal{K}_{-\delta}^1$, such that $B_j = 0$, unless j is odd, and such that, for any $u_0 \in \mathcal{H}_\delta$ and for any $0 < \varepsilon < \varepsilon_0$, as $t \rightarrow \infty$,

$$U(t, 0)u_0 = \sum_j c_j e^{-it\lambda_j} \phi_j(t, x) + t^{-\frac{1}{2}} \left(d_0 \psi(t, x) + \sum_{\ell=1}^m d_\ell \phi_{0\ell}(t, x) \right) + t^{-\frac{3}{2}} B_1 u_0(t, x) + \dots + t^{-\frac{k-2}{2}-1} B_{k-2} u_0(t, x) + O(t^{-\frac{k-2}{2}-1-\varepsilon}),$$

where c_j and $O(t^{-\frac{k-2}{2}-1-\varepsilon})$ are as in Part (1), $d_0 = 2\pi(u_0, \psi(0))_{\mathcal{H}}$, and d_ℓ are linear functionals of u_0 of the form

$$d_\ell(u_0) = a_{\ell 1}(u_0, \phi_{01}(0))_{\mathcal{H}} + \dots + a_{\ell n}(u_0, \phi_{0n}(0))_{\mathcal{H}}, \quad \ell = 1, \dots, m.$$

In particular, all d_ℓ vanish on the orthogonal complement of the 1-eigenspace of the monodromy operator $\mathcal{U}_0 = U(2\pi, 0)$.

The statement in Part (2) is written for the case that we have both a zero threshold resonance and zero eigenvalues. In the other cases obvious modifications are needed.

2 Remarks on the Proof

The proof of Theorem 1.3 is quite long and rather involved. The starting point is a detailed study of the resolvent $R_0(z) = (K_0 - z)^{-1}$, in the form of asymptotic expansions, in the norm topology of the bounded operators $B(\mathcal{K}_\delta^s, \mathcal{K}_{-\delta}^s)$ for $\delta > 1/2$ and $s \geq 0$ an integer. This study is based on the explicit integral kernel of $(-\Delta - z)^{-1}$ on $L^2(\mathbb{R}^3)$. This fact explains why the results depend on the dimension being equal to three. The expansions are needed around every $z \in \mathbb{R}$, the integers being particularly important, since they are the thresholds for our operators K_0 and K .

Let us briefly state some of the results on $R_0(z)$. Using Taylor's theorem the integral kernel of $r_0(z) = (-\Delta - z)^{-1}$ can be expanded as

$$\frac{e^{i\sqrt{z}|x-y|}}{4\pi|x-y|} = \sum_{j=0}^k \frac{1}{4\pi j!} (i\sqrt{z})^j |x-y|^{j-1} + d_k(z; x, y),$$

with the remainder given by

$$d_k(z; x, y) = \frac{(i\sqrt{z})^k |x-y|^{k-1}}{4\pi(k-1)!} \int_0^1 (1-s)^{k-1} (e^{is\sqrt{z}|x-y|} - 1) ds.$$

Using the terms above to define operators we get an expansion

$$r_0(z) = g_0 + \sqrt{z}g_1 + \cdots + z^{k/2}g_k + d_k(z), \quad d_k(z) = \mathcal{O}(z^{\frac{k+\varepsilon}{2}}),$$

in the topology of $B(\mathcal{H}_\gamma, \mathcal{H}_{-\gamma})$, $\gamma > \beta_k = \max\{2k+1, 4\}$, and $0 \leq \varepsilon < \varepsilon_0 = \min\{1, \gamma - \frac{\beta_k}{2}\}$.

Now use $\mathcal{K} = L^2(\mathbf{T}) \otimes \mathcal{H}$, and let p_n denote the projection onto the subspace of $L^2(\mathbf{T})$ spanned by e^{int} . We can then write

$$R_0(z) = (K_0 - z)^{-1} = \sum_{m \in \mathbf{Z}} \oplus p_m \otimes r_0(z - m).$$

Inserting the expansion for $r_0(z)$ we get an expansion

$$R_0(z+n) = R_0^+(n) + \sqrt{z}D_1(n) + \cdots + z^{k/2}D_k(n) + \tilde{R}_{0k}(n, z),$$

where the coefficients can be found explicitly in terms of the g_j 's introduced above.

The next step is the study of $1 + R_0(z)V$. Invertibility of the boundary values of $1 + R_0(\lambda + i0)V$ in $B(\mathcal{K}_\delta^s, \mathcal{K}_{-\delta}^s)$ for $\delta > 1/2$, and $s \geq 0$ an integer, is first studied. The relation to eigenvalues and threshold resonances is also established. Based on the asymptotic expansion of $R_0(z)$ one obtains an asymptotic expansion of $(1 + R_0(z)V)^{-1}$, which then together with the second resolvent equation $R(z) = (1 + R_0(z)V)^{-1}R_0(z)$ yields asymptotic expansions for $R(z)$. We use the technique developed by Murata [5] to obtain these results. One can also use the techniques developed in [4].

The main results can be stated as follows. Here E_n denotes multiplication by e^{int} .

Theorem 2.1. *Let V satisfy the Assumption 1.1 for $\beta > \beta_k \equiv \max\{2k+1, 4\}$, $k \in \mathbf{N}$. Let $\delta = \beta/2$ and $\varepsilon_0 = \min\{1, \frac{\beta - \beta_k}{2}\}$.*

(1) *Suppose that there are no integer eigenvalues or resonances. Then, as a $B(\mathcal{K}_\delta^s, \mathcal{K}_{-\delta}^s)$ -valued function of $z \in \overline{\mathbf{C}}^+$, $s = 0, 1$, for any $0 < \varepsilon < \varepsilon_0$, we have*

$$R(z+n) = F_0(n) + \sqrt{z}F_1(n) + zF_2(n) + \cdots + z^{k/2}F_k(n) + \mathcal{O}(z^{(k+\varepsilon)/2})$$

in a neighborhood of $z = 0$.

(i) $F_j(n) = E_n F_j(0) E_n^*$ for all $n \in \mathbf{Z}$ and $j = 0, 1, \dots$

(ii) *If j is odd, $F_j(0)$ are operators of finite rank and may be written as a finite sum $\sum a_{j\nu} \otimes b_{j\nu}$, where $a_{j\nu}, b_{j\nu} \in \mathcal{K}_{-\delta}^1$.*

(iii) *The first few terms are given as*

$$F_0(n) = G^+(n)R_0^+(n)(= R^+(n)),$$

$$F_1(n) = G^+(n)D_1(n)G^-(n)^*,$$

$$F_2(n) = G^+(n) [D_2(n) - D_1(n)VG^+(n)D_1(n)] G^-(n)^*,$$

where $G^\pm(n) = (1 + R_0^\pm(n)V)^{-1}$, and where $D_j(n)$ are the operators defined in result on the free resolvent.

(2) Suppose that we have either integer eigenvalues, threshold resonances, or both. Then, as a $B(\mathcal{K}_\delta^s, \mathcal{K}_{-\delta}^s)$ -valued function of $z \in \overline{\mathbb{C}}^+$, $s = 0, 1$,

$$R(z+n) = -\frac{1}{z}F_{-2}(n) + \frac{1}{\sqrt{z}}F_{-1}(n) + F_0(n) + \dots$$

$$\dots + z^{(k-2)/2}F_{k-2}(n) + \mathcal{O}(z^{(k-2+\varepsilon)/2})$$

in a neighborhood of $z = 0$. Here

- (i) $F_j(n) = E_n F_j(0) E_n^*$ for $n \in \mathbb{Z}$ and $j = -2, -1, \dots$
- (ii) $F_j(n)$ is of finite rank, when j is odd, and may be written as a finite sum $\sum a_{j\nu} \otimes b_{j\nu}$, where $a_{j\nu}, b_{j\nu} \in \mathcal{K}_{-\delta}^1$.
- (iii) $F_{-2}(n) = E_K(\{n\})$.
- (iv) $F_{-1}(n) = E_K(\{n\})VD_3(n)VE_K(\{n\}) - 4\pi i\bar{Q}_n$, where $\bar{Q}_n = \langle \cdot, \psi^{(n)} \rangle \psi^{(n)}$, and $\psi^{(n)}$ is a suitably normalized n -resonant function.

Now we use the relation

$$e^{-i\sigma K}u = \lim_{\varepsilon \downarrow 0} \lim_{N \rightarrow \infty} \frac{1}{2\pi i} \int_{-N}^N e^{-i\sigma\lambda} R(\lambda + i\varepsilon) u d\lambda,$$

where the right hand side should be understood as a weak integral. It is combined with the asymptotic expansion results, to obtain the following result.

Let $J: \mathcal{H} \rightarrow \mathcal{K}$ be given by $(Ju)(t, x) = u(x)$. We then have the following asymptotic expansion for $e^{-i\sigma K}Ju_0$, $u_0 \in \mathcal{H}_\delta$ (δ sufficiently large).

$$e^{-i\sigma K}Ju_0 = \sum_{j=1}^k \sigma^{-(j+2)/2} \left(\sum_{n \in \mathbb{Z}} e^{-i\sigma n} \varepsilon_j F_j(n) Ju_0 \right) + \mathcal{O}(\sigma^{-\frac{k+2+\varepsilon}{2}})$$

Here $\varepsilon_j = 0$ for j even, and $\varepsilon_j = 1$ for j odd. The expansion coefficients satisfy $F_j(n) = E_n F_j(0) E_n^*$, and

$$F_j(0) = \sum_{\substack{\nu \\ \text{finite}}} f_{j\nu} \otimes g_{j\nu}.$$

By the Sobolev embedding theorem $\mathcal{K}_{-\delta}^1$ is continuously embedded in $\mathcal{H}_{-\delta}$ such that

$$\sup_{t \in \mathbb{T}} \|u(t)\|_{\mathcal{H}_{-\delta}} \leq C \|u\|_{\mathcal{K}_{-\delta}^1}.$$

Using the expansion for $e^{-i\sigma K}$ we get

$$\sup_{t \in \mathbf{T}} \|U(t, t - \sigma)u_0 - \sum_{j=1}^k \varepsilon_j \sigma^{-(j+2)/2} Z_j(\sigma) J u_0(t)\|_{\mathcal{H}_{-\delta}} \leq C \sigma^{-\frac{k+2+\varepsilon}{2}} \|u_0\|_{\mathcal{H}_{\delta}}.$$

Now let $t = \sigma$, and then replace σ by t to get

$$\|U(t, 0)u_0 - \sum_{j=1}^k \varepsilon_j t^{-(j+2)/2} B_j(t) u_0\|_{\mathcal{H}_{-\delta}} \leq C t^{-\frac{k+2+\varepsilon}{2}} \|u_0\|_{\mathcal{H}_{\delta}}.$$

These computations are for the Part (1) of Theorem 1.3. For Part (2) a somewhat more involved argument is needed.

To get the properties of the coefficients stated above we use the following Lemma.

Lemma 2.2. *Let $B = f \otimes g$, $f, g \in \mathcal{K}_{-\delta}^1$. Let $u_0 \in \mathcal{H}_{\delta}$, and let*

$$Z(\sigma)u_0 = \sum_{n=-\infty}^{\infty} e^{-in\sigma} E_n B E_n^* J u_0.$$

Then $Z(\sigma) \in B(\mathcal{H}_{\delta}, \mathcal{K}_{-\delta}^1)$ has the integral kernel

$$2\pi f(t, x) g(t - \sigma, y).$$

Let us briefly outline the proof. We compute as follows, where we use the Fourier inversion theorem in the last step.

$$\begin{aligned} Z(\sigma)u_0 &= \sum_{n=-\infty}^{\infty} e^{-in\sigma} e^{int} f(t, x) \int_{\mathbf{T}} \int_{\mathbf{R}^3} g(s, y) e^{-ins} u_0(y) dy ds \\ &= f(t, x) \sum_{n=-\infty}^{\infty} e^{in(t-\sigma)} \int_{\mathbf{T}} e^{-ins} \left(\int_{\mathbf{R}^3} g(s, y) u_0(y) dy \right) ds \\ &= 2\pi f(t, x) \int_{\mathbf{R}^3} g(t - \sigma, y) u_0(y) dy. \end{aligned}$$

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